RAPID ACQUISITION OF PREFERENCE IN CONCURRENT CHAINS

RANDOLPH C. GRACE, ORN BRAGASON, AND ANTHONY P. MCLEAN

UNIVERSITY OF CANTERBURY

We report two experiments using a concurrent-chains procedure in which one terminal-link schedule was fixed-interval 8 s and the alternative schedule changed randomly from day to day. In Experiment 1, the alternative schedule varied between 4 s and 16 s according to a pseudorandom binary sequence similar to the one used by Hunter and Davison (1985). Similar to results with concurrent schedules, pigeons' response allocation in the initial link was most sensitive to the schedules arranged in the current session, although some effect of prior history was evident. Overall sensitivity was lower than for comparable data from steady-state research. In Experiment 2, a unique value between 2 s and 32 s was used for the alternative-schedule delay in each session. Sensitivity levels were similar to Experiment 1 and remained unchanged across 61 sessions of training. For all subjects, sensitivity was greater when the alternative-schedule delay was greater than 8 s compared with when it was less than 8 s. Generalized-matching plots revealed evidence of clustering of data points into two groups for some pigeons, suggesting that a process similar to a categorical discrimination may have at least partly determined response allocation. Overall, this research shows that pigeons' initial-link response allocation can adjust rapidly to frequent changes in the terminal links.

Key words: acquisition, preference, concurrent chains, key peck, pigeons

---

Most research on choice has examined behavior during the steady state. In a typical study, subjects are given daily sessions with a pair of concurrent variable-interval (VI) schedules until responding stabilizes. The schedules are then changed for the next condition, and so on. The well-known generalized matching relation has been used to describe asymptotic data from these studies (Baum, 1974):

$$\log\frac{B_L}{B_R} = a \log\frac{R_L}{R_R} + \log b, \qquad (1)$$

where B and R indicate response and reinforcer rate, subscripted for left and right choice alternatives. The parameters a and b provide estimates of sensitivity to reinforcer ratio and inherent bias, respectively. Equation 1 has provided an excellent description of the data from concurrent schedules, usually accounting for over 90% of the variance in log relative response rate (Baum, 1979).

The emphasis on steady-state research, however, has begun to be complemented by a growing interest in acquisition—choice in transition. For example, Mazur and colleagues have reported a number of studies on the development of preference under con-

current ratio and interval schedules (Mazur, 1992, 1995, 1997; Mazur & Ratti, 1991). In Mazur's (1992) Experiment 2, subjects were first exposed to concurrent VI VI schedules with equal reinforcement rates. The schedules were then changed such that the overall reinforcement rate remained constant but the relative rates differed. The posttransition schedules were presented for five sessions, by which time preference appeared to have reached an asymptote. Mazur reported that the rate of approach to asymptote was approximately the same for the different reinforcement percentages (60%, 75%, 90%) that he studied.

Some research by Davison and colleagues represents a different approach towards studying choice in transition. Hunter and Davison (1985) attempted to determine a "behavioral transfer function" for pigeons' responding under concurrent VI VI schedules. In their experiment, pigeons were trained with either concurrent VI 60 s VI 240 s or concurrent VI 240 s VI 60 s. Whichever of these pairs was in effect for a given session was determined by a 31-step pseudorandom binary sequence (PRBS). In statistical terms, the PRBS constituted "white noise," so that the reinforcer ratio for a particular session could not be predicted from the previous sessions' values. Hunter and Davison reported an analysis of their results in terms of linear systems theory and found that response ratio

Address correspondence and reprint requests to Randolph C. Grace, University of Canterbury, Department of Psychology, Private Bag 4800, Christchurch, New Zealand (e-mail: r.grace@psyc.canterbury.ac.nz).

in a particular session was largely determined by the reinforcer ratio in that session and to a lesser degree by earlier sessions. Their analysis showed that on average, preference should reach a stable asymptote after three to five sessions of training with a particular set of schedules (cf. Davison & Hunter, 1979).

Davison and McCarthy (1988) reanalyzed Hunter and Davison's (1985) data in terms of an extension of the generalized-matching law:

$$\log \frac{B_{0L}}{B_{0R}} = a_0 \log \frac{R_{0L}}{R_{0R}} + a_1 \log \frac{R_{1L}}{R_{1R}}$$
$$+ a_2 \log \frac{R_{2L}}{R_{2R}} + \cdots + \log b. \quad (2)$$

In Equation 2, the log response ratio in a given session is determined additively by a series of terms representing the reinforcer ratio in the current and prior sessions. The sessions are indicated by the subscripts, with 0 for the current session and 1, 2, . . . for the previous sessions. Each session has an associated sensitivity parameter (a_n). Thus Equation 2 provides a way to describe the influence of reinforcer ratio from the current and prior sessions on choice responding. Davison and McCarthy found that sensitivity (a_0) for the current session (i.e., Lag 0) was greatest, and decreased rapidly to zero by approximately Lag 4.

Schofield and Davison (1997) replicated and extended Hunter and Davison's (1985) work by arranging three different reinforcer ratios and comparing both independent and nonindependent schedules (Stubbs & Pliskoff, 1969). They found that sensitivity (measured either for the current session, Lag 0, or the 10 sensitivities summed across Lags 0 through 9) was unaffected by both the size of the reinforcer ratio and the scheduling arrangement. In Experiment 1, the average of the pigeons' Lag-0 sensitivities for response allocation in the first exposure to the PRBS condition was 0.55 but increased to 0.78 by the third exposure. When cumulated across Lags 0 through 9, average sensitivity increased from 0.86 to 1.18. Thus there was evidence that repeated exposure to a random environment increased sensitivity to current conditions (cf. Davison & Baum, 2000; Gallistel, Mark, King, & Latham, 2001; Mazur,

1997; Shettleworth & Plowright, 1992). Because the sensitivity values were similar to those obtained in steady-state research, Schofield and Davison concluded that the PRBS procedure was a valid technique for quick determination of sensitivity to reinforcer ratio. The validity of this claim would require that individual differences in sensitivity for steady-state and PRBS designs be positively correlated, but this was not tested.

Although it is advantageous to have an efficient method for determining sensitivity, the PRBS procedure may also yield answers to important questions. Examples include the time frame over which recent reinforcement history controls responding, as well as environmental variables that might influence that time frame. A longer-term goal is to determine whether results from the PRBS procedure, as well as from more traditional designs such as the studies of Mazur and colleagues cited above (Mazur, 1992, 1995, 1997; Mazur & Ratti, 1991), can be explained by a single model that might shed light on acquisition processes.

The present research attempts to extend the PRBS design to the concurrent-chains procedure. Here subjects respond during a choice phase ("initial links") to gain access to one of two mutually-exclusive outcome schedules that end in reinforcement ("terminal links"). Because the terminal links are signaled by distinctive stimuli, concurrent chains may be viewed as an extension of concurrent schedules in which conditioned, rather than primary, reinforcement controls choice. The immediacy of primary reinforcement (i.e., the inverse of delay) in the terminal links is a major determiner of preference in the initial link according to most models of concurrent-chains performance (e.g., Fantino, 1969; Grace, 1994; Mazur, 2001).

Exploring whether choice responding in concurrent chains under the PRBS design is similar to concurrent schedules may provide some insight into the effects of delayed reinforcement and the mechanisms underlying choice. Research on discrimination learning suggests that the control of choice by conditioned reinforcement may be less effective than control by primary reinforcement. For example, Williams and Dunn (1991) conducted several experiments in which rats and

pigeons completed a series of reversals of a conditional discrimination. The percentage of reinforcement for correct responses was manipulated across conditions, as were the stimulus conditions following nonreinforced correct responses. Williams and Dunn found that reversals were learned more rapidly when a brief stimulus that accompanied food following reinforced correct responses was also produced by nonreinforced correct responses, compared to when the brief stimulus was not present. The fastest learning, however, occurred during conditions in which 100% of the correct responses were reinforced with food. Earlier studies also suggest that rate of discrimination learning is retarded when reinforcers are delayed, although this effect can be alleviated to some extent by having distinctive cues (i.e., conditioned reinforcers) contingent on the different choice responses (e.g., Carlson & Wielkiewicz, 1972; Grice, 1948).

Evidence that acquisition of preference in concurrent chains may indeed be slower than in concurrent schedules comes from a recent study by Grace (2002). In his Experiment 1, pigeons completed a series of reversals in which the position of the initial-link key leading to the richer terminal-link schedule was varied across successive conditions. All conditions lasted for 20 sessions. Grace studied all possible transitions between different pairs of fixed-interval (FI) and VI schedules and found that a simple linear operator model gave an excellent account of the results. According to this model, rate of acquisition depends on the combined values of the terminal-link schedules, with higher-valued schedule pairs producing both faster acquisition as well as more interference (i.e., retarded acquisition when a low-value schedule pair followed a high-value one). Grace conducted an analysis to determine the number of sessions required to reach 75% of asymptotic preference. For sake of comparison with Davison and Hunter (1979), we reanalyzed Grace's data and found that on average, 13.66 sessions were required to reach 95% of asymptotic preference. This is substantially larger than the four to six sessions to reach similar levels of preference in concurrent schedules reported by Davison and Hunter. This evidence suggests that rate of change in preference in concurrent chains is slower

than corresponding changes in concurrent schedules (see also Mazur, Blake, & McManus, 2001). Thus it is unknown whether pigeons' choice in concurrent chains will track day-to-day changes according to a PRBS design.

We report two experiments in which the delay associated with one terminal link varied unpredictably. Pigeons were trained on a concurrent-chains procedure in which the terminal links were FI schedules signaled by red and green stimuli. The red terminal link was always an FI 8-s schedule, whereas the delay associated with the green terminal link varied from day to day. In Experiment 1, the green-key delay was either 4 s or 16 s, according to the 31-step PRBS used by Hunter and Davison (1985). The PRBS was completed three times. The goal was to determine whether choice would be controlled primarily by the delay in the current session, similar to results with concurrent schedules. In Experiment 2 we explored the effects of using a potentially infinite number of green-key delays.

EXPERIMENT 1

Method

Subjects

Four pigeons of mixed breed, numbered 221 to 224, were maintained at 85% ± 15 g of their free-feeding weights through appropriate postsession feeding. Pigeons were housed individually in a vivarium with a 12: 12 hr light/dark cycle (lights on at 6:00 a.m.), with water and grit freely available in the home cages. Pigeons were experienced with a variety of experimental procedures.

Apparatus

Four standard three-key operant chambers, 32 cm deep by 34 cm wide by 34 cm high, were used. The keys were 21 cm above the floor and arranged in a row 10 cm apart. In each chamber a houselight that provided general illumination was located above the center key, and a grain magazine with a 5 by 5.5 cm aperture was centered 6 cm above the floor. The magazine contained wheat and was illuminated when wheat was made available. A force of approximately 0.15 N was necessary to operate each key. Each chamber was enclosed in a sound-attenuating box, and an

attached fan provided ventilation and white noise. Experimental events were controlled and data recorded through a microcomputer and MED-PC® interface located in an adjacent room.

Procedure

Because the pigeons were experienced, training started immediately in the first condition. The houselight provided general illumination at all times except during reinforcer delivery. With few exceptions, sessions occurred daily and at the same time (10:00 a.m.).

A concurrent-chains procedure was used throughout. Sessions ended after 72 initial- and terminal-link cycles or 70 min, whichever occurred first. At the start of a cycle, the side keys were illuminated white to signal the initial links. An entry was assigned randomly to the left or right terminal link with the constraint that in every six cycles, three entries occurred to each terminal link. An initial-link response produced an entry into a terminal link if (a) it was made to the preselected key, (b) an interval selected from a VI 10-s schedule had timed out, and (c) a 1-s changeover delay (COD) was satisfied—that is, at least 1 s had elapsed following a changeover to the side for which terminal-link entry was arranged.

The VI 10-s initial-link schedule did not begin timing until the first response had occurred in each cycle, to allow any pausing after the completion of the previous terminal link to be excluded from initial-link time. The VI 10-s schedule contained 12 intervals constructed from an exponential progression (Fleshler & Hoffman, 1962). Separate lists of intervals were maintained for cycles in which the left or right terminal link had been selected and were sampled without replacement so that all 12 intervals would be used three times for both the left and right terminal links each session.

Upon entry into a terminal link, the color of the side key was changed (left key to red, right key to green), and the other key was darkened. Terminal-link responses were reinforced according to FI schedules. When a response was reinforced, all lights in the chamber were extinguished, and the grain magazine raised and illuminated for 3 s.

The FI schedule value for the red (left) ter-

Table 1

FI schedule values (in seconds) used for the green (right-key) terminal link in Experiment 1. The delays were defined according to the 31-step PRBS used by Hunter and Davison (1985). The values listed below were used for Pigeons 222 and 224; the values were reversed (i.e., 16 s = 4 s and vice versa) for Pigeons 221 and 223.

Step	Delay
1	16
2	4
3	4
4	4
5	16
6	16
7	4
8	16
9	16
10	16
11	4
12	16
13	4
14	16
15	4
16	4
17	4
18	4
19	16
20	4
21	4
22	16
23	4
24	16
25	16
26	4
27	4
28	16
29	16
30	16
31	16

minal link was always 8 s, and the value for the green (right) terminal link was either 4 s or 16 s across sessions according to a PRBS, as specified in Table 1. The PRBS consisted of 31 steps and was the same as that used by Hunter and Davison (1985), with some minor deviations. Owing to experimenter error, the delays for the second and third sequences differed slightly from the series used by Hunter and Davison. In the second sequence, the delays for the 18th and 20th steps were reversed (i.e., 4 s rather than 16 s or vice versa), and in the third sequence, the delays for the 8th through 14th steps were programmed for the 7th through 13th steps. The experiment lasted for 93 sessions, so that the subjects were exposed to the pseudorandom sequence three times.
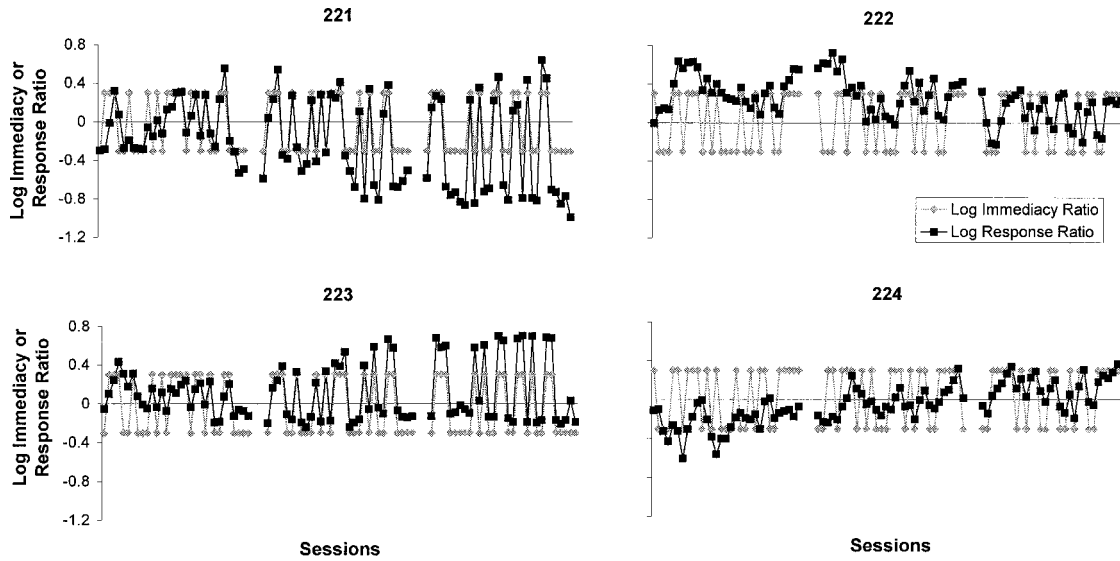
Fig. 1.   Log initial-link response ratios and log terminal-link reinforcement immediacy ratios across the three PRBS presentations in Experiment 1. Small gaps in the figure indicate the end of PRBS presentations one and two.

RESULTS AND DISCUSSION

Figure 1 plots the log initial-link response and terminal-link immediacy ratios (left key divided by right key) for all subjects across the three presentations of the PRBS. Each data point represents performance in a single session. Individual differences are evident in Figure 1. For example, responding for Pigeons 221 and 223 appears to be more sensitive to the immediacy ratio, as evidenced by greater shifts in preference from session to session, than corresponding data for Pigeons 222 and 224. Response patterns for all subjects, however, appeared to track the immediacy ratio by the third PRBS presentation. Left-key and right-key biases were evident in the first PRBS presentation for Pigeons 222 and 224, respectively, although these biases appeared to be largely eliminated by the third presentation.

For a quantitative assessment of the degree to which the immediacy ratios from the current and previous sessions controlled choice, a generalized-matching model similar to Equation 2 was applied to the data:

$$\log\frac{B_{0L}}{B_{0R}} = a_0\log\frac{1/D_{0L}}{1/D_{0R}} + a_1\log\frac{1/D_{1L}}{1/D_{1R}}$$
$$+ a_2\log\frac{1/D_{2L}}{1/D_{2R}} + \cdots + \log b. \quad (3)$$

In Equation 3, B is initial-link response rate and D is terminal-link reinforcement delay, subscripted for both choice alternative (L and R) and lag (0 through 9). The parameters $a_0 \ldots a_9$ represent sensitivity to reinforcement immediacy (i.e., reciprocal of delay) at each lag, and b is inherent bias. Multiple regression analyses were conducted to estimate sensitivity coefficients from Lag 0 (i.e., current session) through Lag 9. Separate analyses were conducted for the three PRBS presentations. Because the obtained delays were quite close to those programmed in all cases, the multiple regressions were based on the programmed delay ratios.

Figure 2 shows the sensitivity coefficients for all lags across the three PRBS presentations. For all subjects, Lag 0 sensitivity increased across the presentations and for the second and third was the greatest sensitivity at any lag. For the third sequence, Lag 0 sensitivities varied from 1.84 for Pigeon 221 to 0.47 for Pigeon 224. This confirms the general impression from Figure 1 that there were individual differences in sensitivity and that responding became more sensitive to the immediacy ratio in the current session with increased training.

Schofield and Davison (1997) found that Equation 2 provided an excellent fit to their data, accounting for more than 95% of the
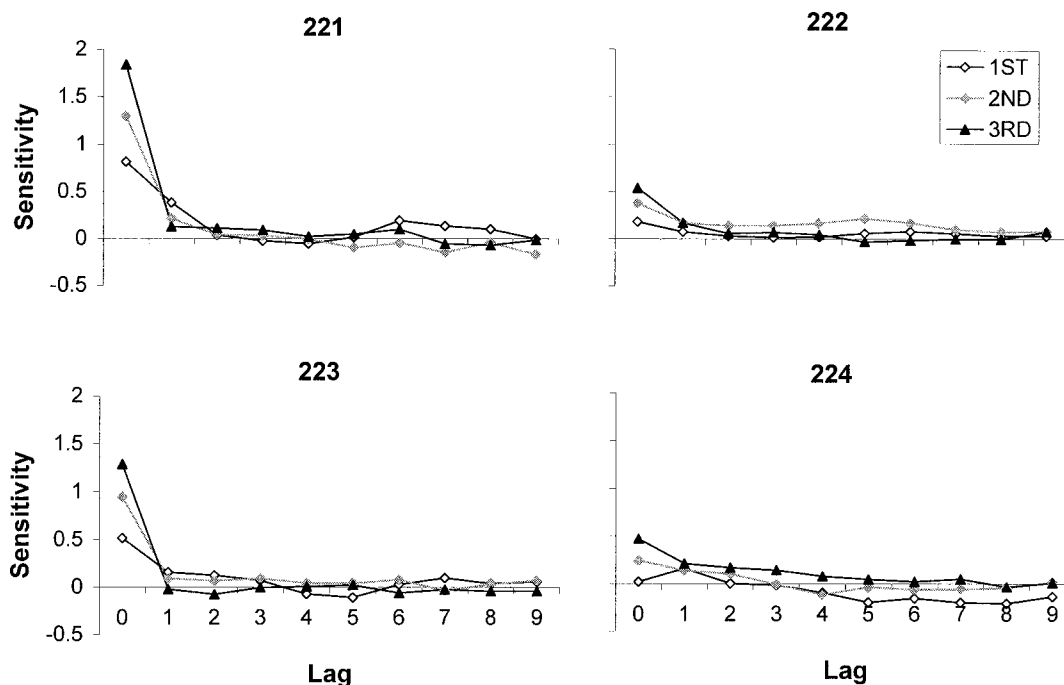
Fig. 2.   Sensitivity to immediacy for Lag 0 through Lag 9 for each PRBS presentation in Experiment 1. The PRBS presentations are marked as noted in the legend.

variance in 35 out of 36 cases, including subjects' first exposure to the PRBS procedure. Equation 3 performed somewhat less successfully for the present data, accounting for an average of only 83% and 66% of the variance in the first two PRBS presentations. For the third, however, the average variance accounted for increased to 94%, and was greater than 90% for all subjects. This suggests that pigeons may require more training in concurrent-chain schedules than in concurrent schedules before responding tracks a terminal-link schedule that changes daily, but that control over choice does develop.

The PRBS design makes it possible to determine the number of previous sessions over which the green-key FI schedule values continue to exert an influence over responding in the current session. Schofield and Davison (1997) reported several different analyses to address the question for their procedure, including the average number of sessions for which the lagged sensitivities are greater than zero, and the lag at which the sensitivity cumulated until that lag is equal to (or greater than) the sensitivity cumulated across all lags. We applied their analyses to the present data

with the following results. (a) The average number of sessions for which the lagged sensitivities were positive was 4.0, 5.0, and 4.25 for the three PRBS presentations, respectively. These values are similar to those reported by Schofield and Davison, which ranged from 4.2 to 5.7. (b) The average lag value for which cumulated sensitivity was equal to or greater than the sensitivity cumulated across all 10 lags was 6.5, 4.5, and 5.25 for the three PRBS presentations. Again, these are similar to Schofield and Davison's results, which ranged from 5.2 to 5.8. One final method is to determine the number of lag coefficients that are statistically significant. We report this analysis only for the third sequence, for which Equation 3 provided an excellent fit for all subjects. For Pigeons 221 and 223, only the Lag 0 coefficient was significant. Lag 0 and Lag 1 were significant for Pigeon 222, and Lags 0 through 3 were significant for Pigeon 224. Thus by the third PRBS presentation preference was largely determined by the immediacy ratio in the current session, although there were still detectable effects of previous sessions that varied across subjects. All of these results are consistent with those
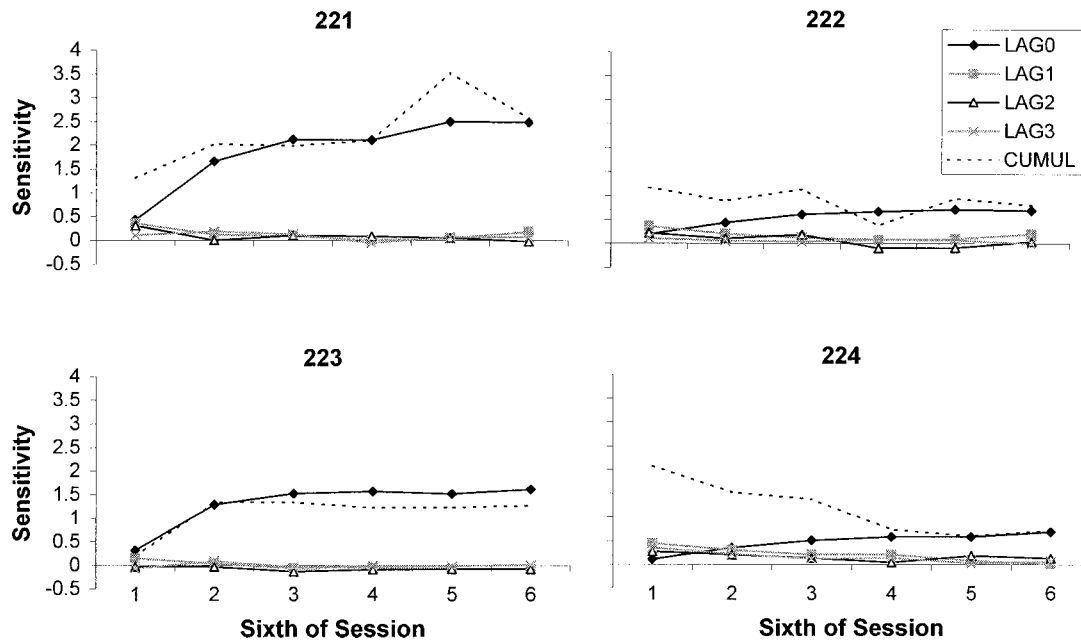
Fig. 3.   Sensitivity to immediacy for Lags 0 through 3 determined separately for each session sixth. Cumulative sensitivity (Lags 0 through 9) is shown by the dashed line. Data are from the third PRBS presentation in Experiment 1.

of Hunter and Davison (1985) and Schofield and Davison for concurrent schedules.

Davison and McCarthy (1988) suggested that the sensitivity cumulated across all lags might serve as an estimate of overall sensitivity to reinforcement. Schofield and Davison (1997) found that their cumulative sensitivity values were similar to sensitivity parameters obtained in parametric steady-state designs (0.86 for response allocation and 1.04 for time allocation, respectively). This suggests that the PRBS procedure, in which sensitivity to reinforcement can be determined in a single condition, might be used instead of traditional designs requiring four or five conditions for rapid determination of sensitivity to reinforcer ratio. One question posed by the present research is whether an analogous result would hold for concurrent chains.

To address this issue, we computed the cumulative sensitivities for all subjects for the third PRBS presentation. The values were: Pigeon 221: 2.19; Pigeon 222: 0.91; Pigeon 223: 1.05; and Pigeon 224: 1.18. With the exception of Pigeon 221, these values are generally low compared with steady-state research: Grace (1994) reported that average sensitivity values for 12 studies using FI terminal links in concurrent chains was 2.68.

One explanation for the relatively low cumulative sensitivity values is that preference for the shorter terminal link developed gradually over the course of the session. If this were true, then the cumulative sensitivities reported above might reflect aggregating across nonhomogeneous responding. Thus we repeated the multiple regression analysis for the third PRBS presentation separately for data from successive sixths (12-reinforcer blocks) of each session. The results are shown in Figure 3 (for Lags 0 through 3, as well as cumulated across all 10 lags). For all subjects, Lag 0 sensitivity increased over the course of the session, and Lag 1, 2, and 3 sensitivities generally decreased. By the end of the session, sensitivity at Lag 0 was approximately equal to the cumulative sensitivity, indicating no contribution of earlier sessions—that is, that control was entirely based in the current session. This indicates that response allocation changed in a systematic way during the session. The subjects, however, showed two distinct patterns of adaptation.

For Pigeons 221 and 223, cumulative sensitivity increased across the session, driven largely by Lag 0 sensitivity (which was greater for these 2 pigeons than it was for Pigeons 222 and 224). There was relatively substantial
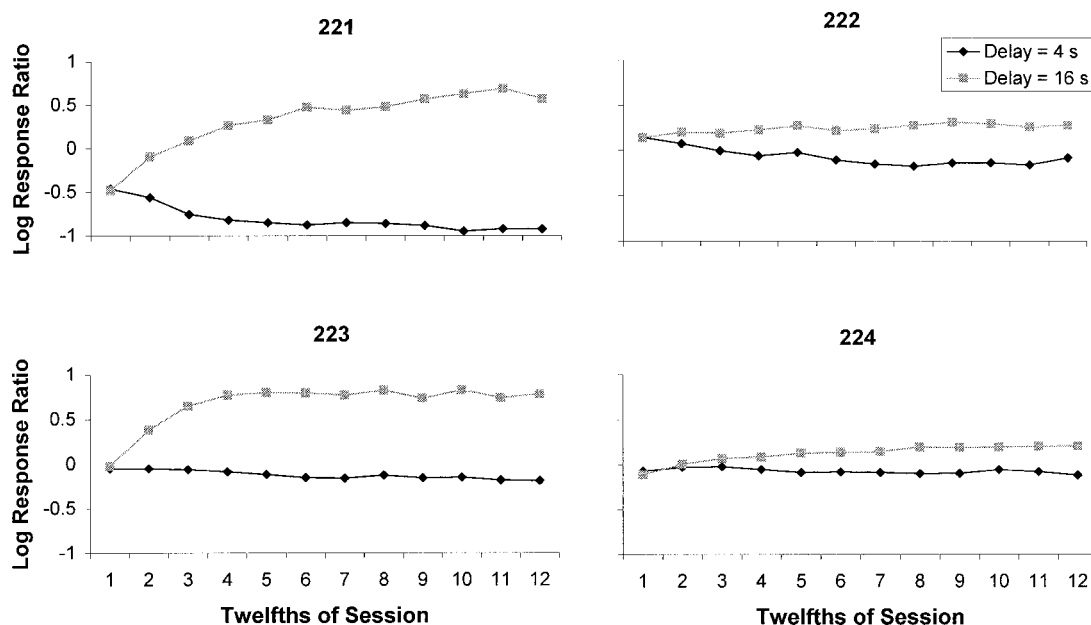
Fig. 4. The log initial-link response ratio across successive twelfths of the session, shown separately for sessions in which the green-key FI schedule value was 4 s and 16 s. Data are from the third PRBS presentation in Experiment 1.

control by previous sessions during the first sixth for Pigeon 221, as evidenced by a cumulative sensitivity greater than 1 and sensitivity coefficients that were statistically significant for both Lags 1 and 2 (in addition to Lag 0). There was rather less control by prior sessions for Pigeon 223, as demonstrated by a cumulative sensitivity near zero. The Lag 1 coefficient, however, was still statistically significant during the first sixth for this pigeon (in addition to Lag 0).

Responding changed in a different way for Pigeons 222 and 224. Cumulative sensitivity decreased across the session until it was approximately equal to Lag 0 sensitivity. The pattern was especially dramatic for Pigeon 224, where the cumulative sensitivity during the first sixth was 2.09. Sensitivity coefficients were statistically significant up to Lag 5 and were positive for all lags. In contrast, the maximum Lag-0 sensitivity attained in the final sixth was 0.69. This shows that for Pigeon 224 there was strong control of responding by prior history early in the session, but this weakened over the course of the session and the current immediacy ratio acquired control. Because prior history (up to five previous sessions) would again show control at the start of the next session, this phenomenon is similar to spontaneous recovery (cf. Mazur, 1995).

One disadvantage of the multiple regression analyses reported here is that they do not distinguish between sessions in which the green-key FI schedule was 4 s and ones in which it was 16 s. Yet responding may adapt differently depending on whether the varied delay is shorter or longer than the delay that is constant across sessions (i.e., FI 8 s). Figure 4 shows log response ratio across successive twelfths of the session, separately for sessions in which the green-key delay was 4 s and 16 s. The data are taken from the third PRBS presentation. No subject responded differentially during the first twelfth of the session (i.e., six terminal link cycles), although Pigeon 221 showed a strong bias towards the right key, which was associated with the green terminal link. Responding for Pigeon 222 was slightly biased towards the left key (red terminal link), whereas Pigeons 223 and 224 showed virtually no bias.

For all subjects, response allocation shifted in favor of the shorter delay across the session for both 4-s and 16-s green-key delays. The extent of change for the 4-s and 16-s sessions, however, varied. Measured as the difference between the first and twelfth data point and

expressed so that positive values indicate stronger preference for the shorter delay, the extent of change for 4-s and 16-s green-key sessions, respectively, were: Pigeon 221: 0.46, 1.06; Pigeon 222: 0.23, 0.14; Pigeon 223: 0.14, 0.81; and Pigeon 224: 0.07, 0.42. For 3 of 4 pigeons (the exception being Pigeon 222), the magnitude of the shift towards the short delay was substantially greater for 16-s compared with 4-s green-key sessions. For Pigeon 222, the shift was somewhat larger for the 4-s sessions, although the difference was small compared with the other pigeons.

The larger shifts overall when the green-key schedule was FI 16 s suggest that the log immediacy ratio may not have been the sole variable controlling choice, as assumed by Equation 3. Because the log immediacy ratios for 4-s and 16-s green-key delays differed only in sign, the effect on behavior should have been equivalent, though opposite in direction. Yet the discrimination between FI 8 s and FI 16 s produced a greater change within session than that between FI 8 s and FI 4 s. This is consistent with the so-called "terminal-link effect," in which preference between a pair of schedules in constant ratio becomes more extreme as their absolute duration increases (MacEwen, 1972; Williams & Fantino, 1978). This comparison may be problematic, however, because these prior studies examined steady-state behavior, not choice in transition.

Another possibility is that specific response patterns, analogous to decision rules, emerged to control choice. For example, Pigeon 223 responded about equally to both initial links, unless the green-key delay was 16 s, in which case allocation sharply shifted to the left key (see Figure 4). This pattern might be summarized as "avoid the long delay." The strong bias towards the right key shown by Pigeon 221 at the start of the session, coupled with a rapid shift towards the left when the delay was 16 s, suggests an effective strategy of "assume the delay is 4 s; if not, switch to the left key." Although these interpretations are speculative, the different patterns of adaptation to 4-s and 16-s green-key delays pose a difficulty to any account of responding in the PRBS procedure purely in terms of the log immediacy ratio.

Although the second and third PRBS sequences differed slightly from the first, there is no reason to suspect that this discrepancy compromised the results in any way. The multiple regressions were based on the delays that were actually programmed, and so the differences between the sequences posed no difficulty in terms of performing the analyses. The second and third sequences were less balanced in terms of the green-key delays: For the first PRBS sequence, there were 15 sessions with 4 s and 16 sessions with 16 s for Pigeons 222 and 224, compared with 13 sessions with 4 s and 18 sessions with 16 s for the second and third sequences. But the delays were counterbalanced in each session across pigeons, so that the sequences for Pigeons 221 and 223 were imbalanced in the opposite way. Moreover, individual differences in sensitivity were consistent, with Pigeons 221 and 223 showing the greatest sensitivity to Lag 0 immediacy across all three sequences. Thus it is unlikely that the differences between the sequences affected the results.

Overall, these results show that response allocation in the initial links of concurrent chains can be controlled primarily by the terminal-link FI schedules in the current session when one of those schedules changes unpredictably from day to day. Reinforcement immediacy from previous sessions has a measurable effect on responding, especially early in the session (Figure 3). By the last sixth of the session, however, there was little influence of history; behavior was almost exclusively controlled by the current schedule parameters. One important caveat, though, is that compared with Schofield and Davison's (1997) results with concurrent schedules, the sensitivity cumulated across lags (with the exception of 1 subject) fell short of typical values obtained with steady-state research.

EXPERIMENT 2

Experiment 1 demonstrated that response allocation could come under control of the green-key delay when it varied unpredictably across sessions between 4 s and 16 s. One limitation, however, was that only a single pair of relative immediacy values was used. Because changes in response allocation within session were overall greater with 16-s than 4-s green-key delays (see Figure 4), the pigeons' behavior may not have been controlled by the immediacy ratio. Thus it is impossible to know

whether the Lag 0 coefficients reflected true *sensitivity* to relative immediacy, as opposed to a systematic response pattern (e.g., avoid the long delay). Such patterning might explain why the cumulative sensitivity coefficients diverge from those obtained in steady-state research (cf. Baum, Schwendiman, & Bell, 1999).

One way to discover whether relative immediacy can control preference in a variable environment is to increase the number of green-key delays. In Experiment 2, the FI schedule values for the green key were determined pseudorandomly from session to session, such that they varied between 2 s and 32 s and were logarithmically distributed (i.e., the log schedule values were uniformly distributed). In this way, the resulting range of possible immediacy ratios was 1:4 to 4:1, and ratios were uniformly distributed (in logarithmic terms) around 1:1. At issue was whether response allocation would be a continuous function of the immediacy ratio, or if subjects would respond differently depending on whether the green-key delay was less than or greater than 8 s, as would be expected from a response strategy. Also of interest was whether an equivalent degree of control over responding would be observed as in Experiment 1.

METHOD

Subjects

The same pigeons used in Experiment 1 served as subjects.

Apparatus

Same as Experiment 1.

Procedure

Training for Experiment 2 began immediately after the completion of Experiment 1 and lasted for 61 sessions. The concurrent-chains procedure was identical in all respects to that used in Experiment 1, except that a different FI schedule value for the right terminal link (i.e., green key) was used in each session. Green-key delays were the same for all subjects in each session, and were determined as follows. The pseudorandom number tool in Microsoft® Excel was used to generate a list of random numbers that were uniformly distributed between 1 and 5. The antilog (base 2) of each number was then tak-

en, yielding a distribution of numbers between 2 (2^1) and 32 (2^5), with approximately half the values less than 8 (i.e., 2^3). These numbers were used as the FI schedule values for the green-key terminal link for all subjects.

The list of green-key schedule values is provided in the Appendix. The geometric mean value was 7.34; the arithmetic mean was 9.65. Thirty-two of the values were less than 8 s; twenty-nine were greater than 8 s.

RESULTS AND DISCUSSION

Figure 5 shows the log initial-link response ratios and log terminal-link immediacy ratios for each session in Experiment 2. Apparently all pigeons could track changes in the immediacy ratio, although individual differences were evident. For example, data for Pigeon 221 show the most extreme changes in responding, as in Experiment 1. It is unclear whether sensitivity to immediacy changed across sessions.

To determine whether response allocation was becoming more sensitive to the immediacy ratio across the course of training, we conducted a series of generalized-matching analyses using the following equation:

$$\log\frac{B_L}{B_R} = a \log\frac{1/D_L}{1/D_R} + \log b. \qquad (4)$$

For each consecutive block of 10 sessions, the sensitivity to relative immediacy (a in Equation 4) was determined by linear regression. The results are shown in Figure 6. For all pigeons, sensitivity did not change systematically over the course of training. Thus for all subsequent analyses we pooled the data across the 61 sessions.

One question posed by Experiment 2 was whether response allocation could still be controlled by the immediacy ratio in the current session when the green-key delay was completely random and not restricted to two values. A multiple regression analysis using Equation 3 was carried out. The sensitivity coefficients for each lag are shown in Figure 7. Sensitivity was greatest at Lag 0 for each pigeon, and decreased afterwards for greater lags. The largest Lag-0 coefficient was once again obtained for Pigeon 221, confirming the visual impression from Figure 6.

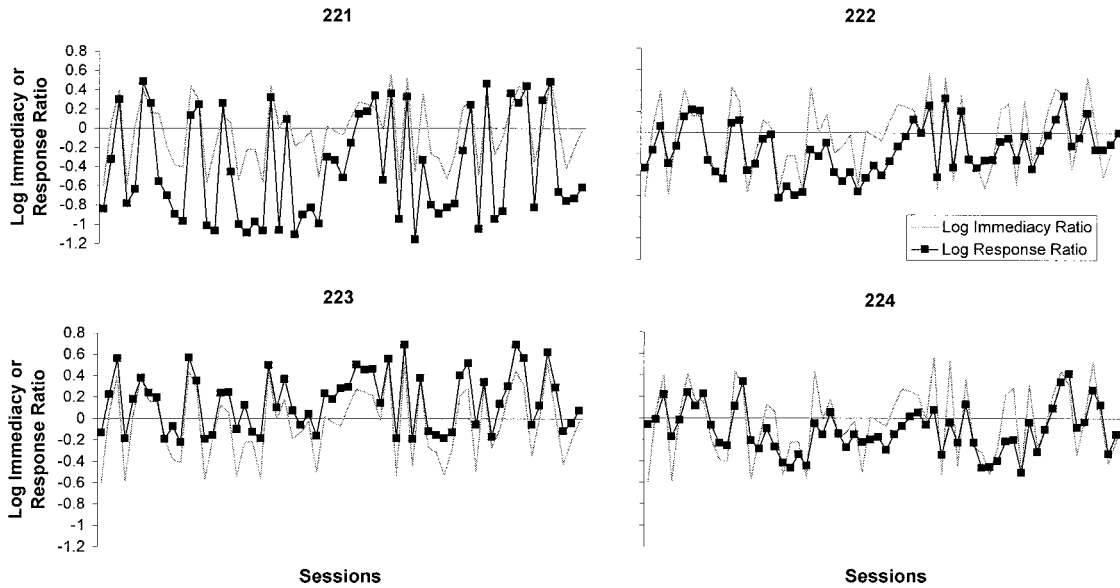The variance accounted for by Equation 3 varied across subjects. The values were: Pi-

Fig. 5.   Log initial-link response ratios and log terminal-link reinforcement immediacy ratios for Experiment 2.

geon 221, 79%; Pigeon 222, 82%; Pigeon 223, 93%; and Pigeon 224, 76%. With the exception of Pigeon 223, these values are lower than those obtained for the third PRBS presentation in Experiment 1. This might be attributed to the greater variation in log immediacy ratios in Experiment 2.

Next we conducted a set of further analyses to determine the extent to which prior ses-

sions controlled behavior. The average number of lags for which the coefficients remained positive was 5.5. The average lag for which sensitivity cumulated until that lag was greater than or equal to sensitivity cumulated across all 10 lags was 6.0. The coefficients for Lag 0 through 2 were statistically significant for Pigeon 222, Lag 0 and 1 coefficients were significant for Pigeons 223 and 224, and only
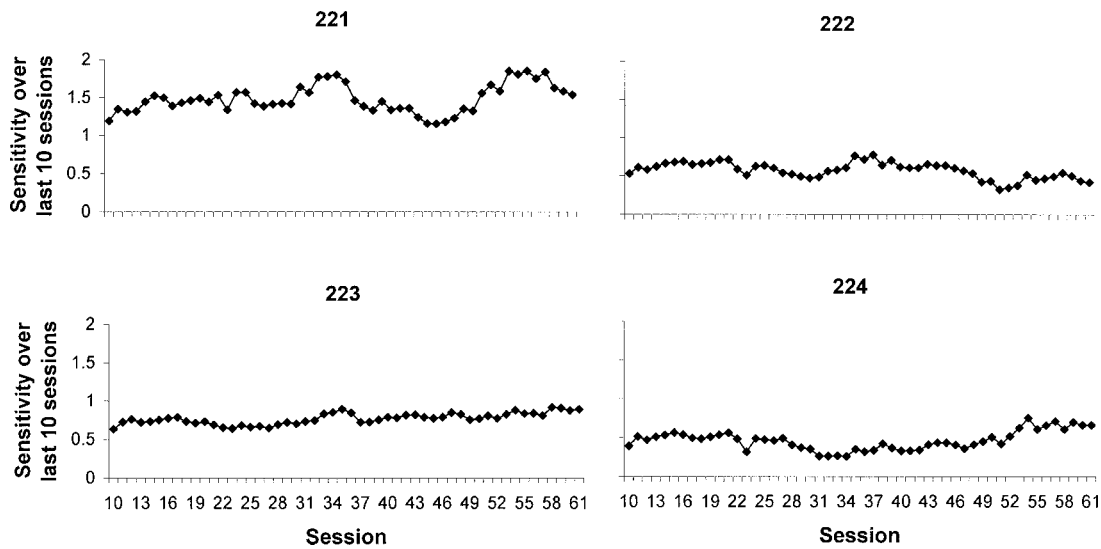

Fig. 6.   Sensitivity to reinforcement immediacy over the last 10 sessions in Experiment 2. Sensitivity values were determined using Equation 4, and are shown for sessions 10 through 61.
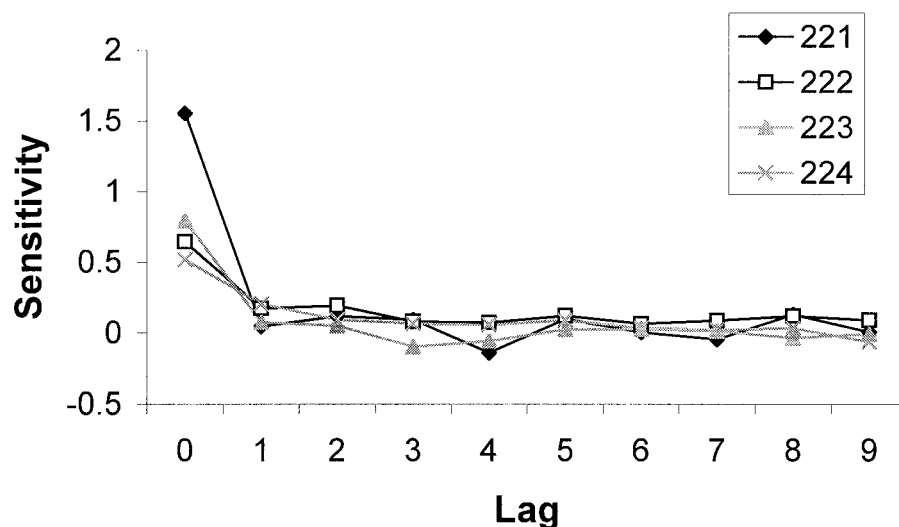
Fig. 7.   Sensitivity to immediacy for Lag 0 through Lag 9 in Experiment 2. Data for individual subjects are noted in the legend.

Lag 0 was significant for Pigeon 221. All of these results are similar to those obtained in Experiment 1, and suggest that response allocation was largely controlled by the immediacy ratio in the current session, although several prior sessions' influence was detectable.

We also wanted to test whether sensitivity cumulated across all lags would be approximately equal to sensitivity values obtained in traditional steady-state designs, as Schofield and Davison (1997) reported for concurrent schedules. The cumulative sensitivity values were: Pigeon 221, 1.87; Pigeon 222, 1.65; Pigeon 223, 0.80; and Pigeon 224, 1.06. As in Experiment 1, these values are lower than those commonly obtained in steady-state designs with FI terminal links (Grace, 1994).

To determine whether sensitivity changed systematically within sessions, we analyzed data by each session sixth. Results are shown in Figure 8 for Lags 0 through 3, and cumulated across Lags 0 through 9. Similar to Experiment 1, Lag 0 sensitivity began at a low level for all subjects and increased during the session. Sensitivities for Lags 1 through 3 also decreased after the first sixth. In contrast to Experiment 1, cumulative sensitivity did not change systematically for any subject, although there is some evidence that Pigeons 221 and 224 showed increasing and decreas-

ing trends, respectively, as these pigeons did in Experiment 1 (cf. Figure 3).

Overall, the results of the preceding analyses are similar to Experiment 1 and suggest that choice was controlled by the green-key delay to about the same degree, regardless of whether the delay was sampled from two values or an infinite population of values.

A major purpose of Experiment 2 was to determine whether responding would be a continuous function of the green-key delay. Such a result is implied by models for choice such as Grace's (1994) contextual choice model and Mazur's (2001) hyperbolic value-added model. According to these models, choice in the initial links is determined by the value of the terminal-link schedules, where value is a continuous function of reinforcement delay. The process that determines value should be the same regardless of whether the green-key delay was less than or greater than 8 s.

We conducted two analyses to determine whether responding was a continuous function of the green-key delay. First, we computed sensitivity to relative immediacy by applying Equation 4 to the data from each sixth of the session. Data were divided into two sets depending on whether the green-key delay was less than or greater than 8 s. Figure 9 shows the sensitivity values separately for the
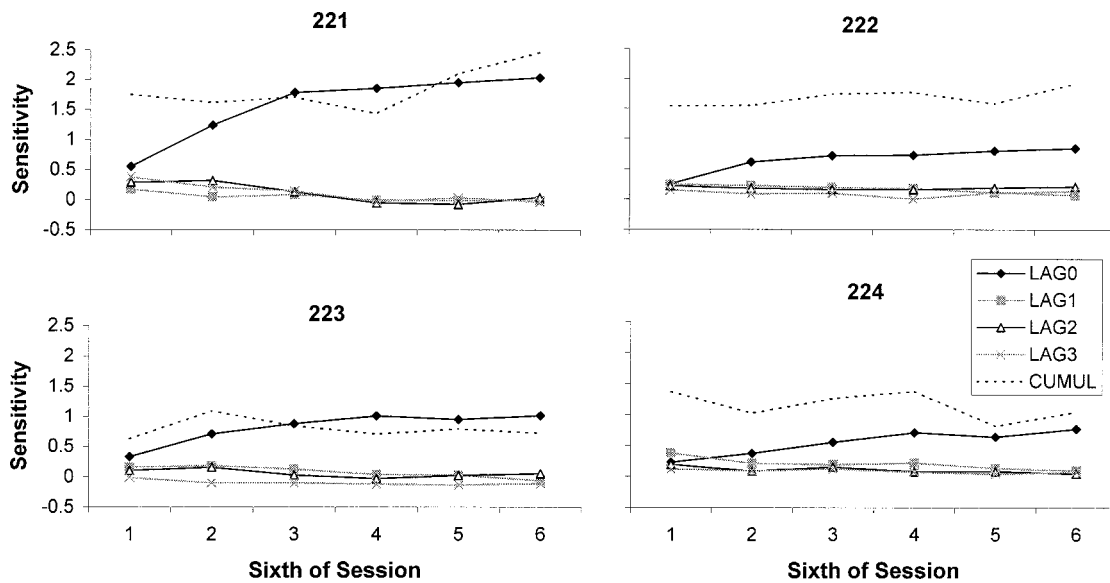
Fig. 8. Sensitivity to immediacy for Lags 0 through 3 determined separately for each session sixth in Experiment 2. Cumulative sensitivity (Lags 0 through 9) is shown by the dashed line.

two sets. In every comparison (24 out of 24 cases), sensitivity was greater when the green-key delay was greater than 8 s. Moreover, sensitivity increased within sessions in seven out of eight cases (the exception being Pigeon 221, delays < 8 s).

To provide a more detailed examination of the change in sensitivity within sessions, Figure 10 plots the log initial-link response ratio as a function of the log green-key delay for the first and sixth session sixths. Shown in all panels are regression lines computed sepa-
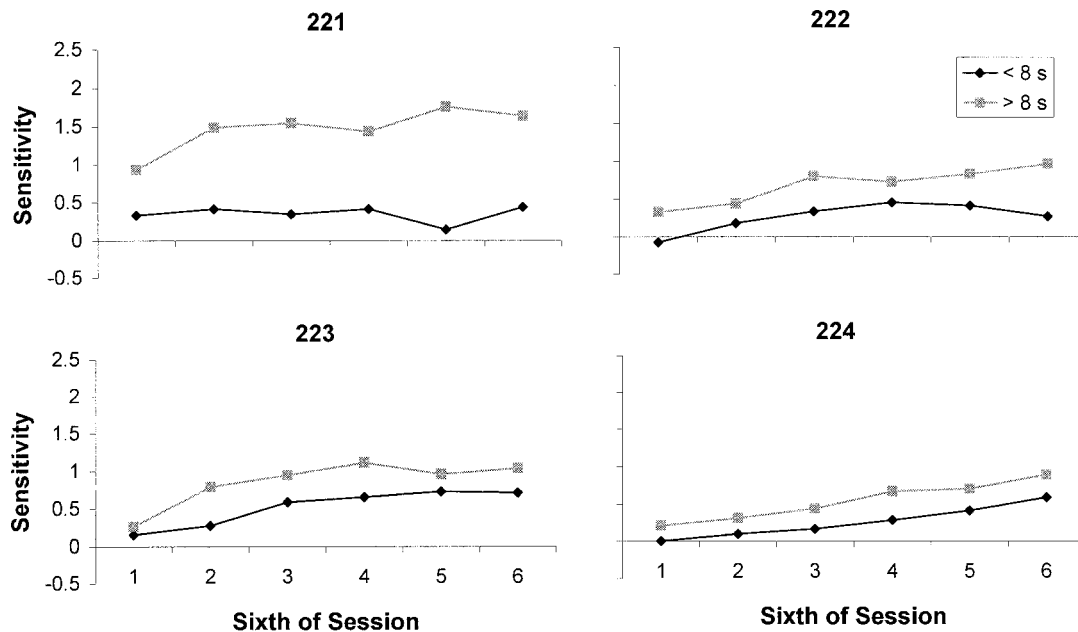

Fig. 9. Sensitivity to immediacy shown separately for sessions in which the green-key delay was less than or greater than 8 s, for each session sixth in Experiment 2. Sensitivity values were determined using Equation 4.
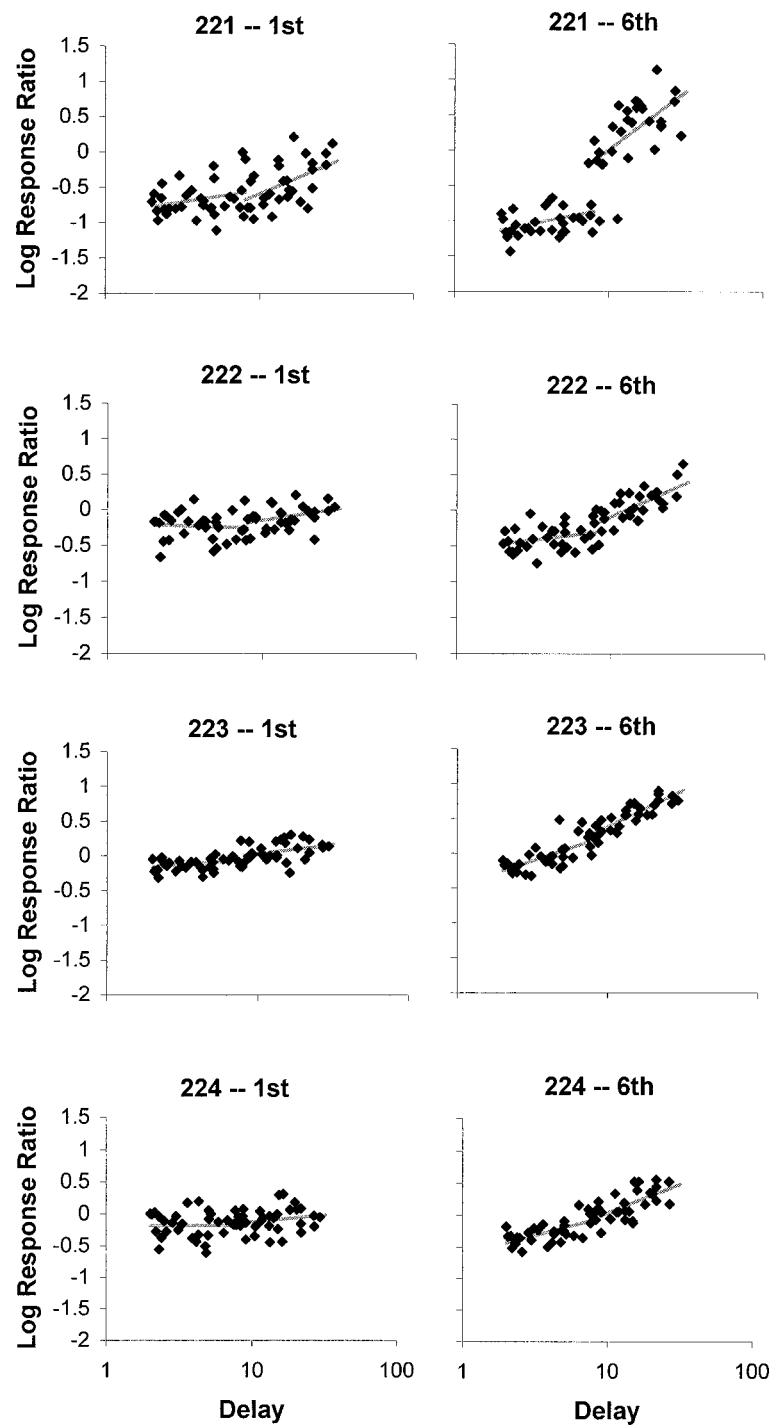
Fig. 10.   Scatterplots of the log initial-link response ratio as a function of the log green-key delay, shown for both the first sixth (left panels) and last sixth (right panels) of each session. Each data point indicates responding from a single session. The lines in the right panels indicate best-fitting regressions estimated separately for delays that were less than or greater than 8 s.

rately depending on whether the delay was less than or greater than 8 s. Figure 10 shows that at the start of a session (left panels), responding was largely undifferentiated; the data points have a great deal of scatter. Nevertheless, for all subjects the regression slope (which measures sensitivity to relative immediacy) was steeper when the delay was greater than 8 s, consistent with Figure 9. By the last sixth of the session (right panels), the slopes increased for all subjects, as well as the size of the difference in slopes depending on whether the delay was less than or greater than 8 s.

Apart from the increases in slope across the session, there is also a tendency for the data points to fall into two separate clusters. This pattern is especially pronounced for Pigeon 221, where the two clusters are well separated. Pigeon 221 also demonstrates the largest difference in sensitivity depending on whether or not the delay was less than 8 s. Although the separation is not nearly so dramatic, arguably there is some evidence of similar clustering for the other pigeons (e.g., Pigeon 222).

The clustering of data points is consistent with the notion that the process determining choice in Experiment 2 resembled a categorical discrimination. One of two response patterns emerged, depending on whether the green-key delay was less than or greater than 8 s. Additional evidence in support of this view is that for some of the pigeons, delays greater than 8 s sometimes were "miscategorized." For example, for Pigeon 221 the log response ratio for one delay greater than 10 s falls into the cluster with the shorter delays. In any event, Figures 9 and 10 strongly suggest that delays less than and greater than 8 s did not have equivalent but opposite effects, as would be expected if the immediacy ratio were the controlling variable. Instead, all pigeons showed some evidence of differential sensitivity, depending on whether the green-key delay was less than or greater than 8 s.

GENERAL DISCUSSION

The present research demonstrates that response ratio during the initial links of concurrent chains can adjust far more rapidly to changes in the terminal links than previous studies have shown. In Experiment 1, the green-key terminal-link FI schedule was varied between 4 s and 16 s according to a PRBS, whereas the red-key schedule was always FI 8 s. Sensitivity to the log immediacy ratio in the current session (Lag 0) increased across the three PRBS presentations and was consistently larger than sensitivity coefficients for the preceding nine sessions (i.e., Lags 1 through 9). For the third PRBS presentation, the average variance accounted for by a generalized-matching model was 94%. These results are similar to those obtained with concurrent schedules (Schofield & Davison, 1997).

Sensitivity to relative immediacy in Experiment 1, cumulated across lags, was less than that obtained in steady-state research, however. Schofield and Davison (1997) reported that cumulative sensitivity in their procedure was approximately equal to steady-state values. Averaged across subjects, cumulative sensitivity in Experiment 1 was 1.33, which is substantially lower than the value of 2.68 reported by Grace (1994) as the sensitivity to relative immediacy averaged across 12 archival studies of preference in concurrent chains with FI terminal links. The relatively small cumulative sensitivity may suggest that control of choice by conditioned reinforcers is weaker than by primary reinforcers or that the conditioned values of the terminal-link stimuli do not reach asymptotic levels when schedules are changed every session.

A finding inconsistent with Equation 3 was that relative initial-link responding in Experiment 1 changed to a greater extent within session when the green-key delay was 16 s rather than 4 s. Although individual pigeons differed, this pattern was dramatic for some pigeons (see, e.g., Pigeon 223 in Figure 4). Whatever the explanation for this result may be, one implication is that the reinforcement immediacy ratio may not control choice in a simple way. Because the log immediacy ratios were equal but opposite in sign depending on whether the green-key delay was 4 s or 16 s, Equation 3 would predict equal but opposite effects on behavior.

Experiment 2 tested the effects of using a wide range of immediacy ratios. The green-key delay across sessions was determined pseudorandomly such that it varied between 2 s and 32 s, and log immediacy ratios were evenly distributed around 1:1 (i.e., 8-s green-key delay). Control over responding by the

current session's delays was approximately the same as in Experiment 1 right from the beginning. No systematic changes in sensitivity occurred during the course of training in Experiment 2. The Lag-0 and cumulative sensitivity coefficients were not systematically different from Experiment 1 (Figures 2 and 7).

Sensitivity to relative immediacy in Experiment 2, however, was greater when the green-key delay was greater than 8 s than when it was less than 8 s. This difference was obtained for all pigeons across each session sixth (Figure 9). This implies that subjects may not have been making a discrimination simply on the basis of the log immediacy ratio. More provocative was the apparent clustering of data points into two groups by the last sixth of the session (Figure 10). This clustering was clearly obtained for Pigeon 221, although data for the other subjects showed a tendency towards it. The clustering in Pigeon 221's data is consistent with a categorical discrimination in which differential responding would occur depending on whether the green-key delay was greater or less than 8 s.

This finding has potential implications for theoretical accounts of choice. Although the empirical validity of the generalized matching law and related models as descriptors of choice is well established (Baum, 1974, 1979; Davison, 1983; Grace, 1994; Logue, Rodriguez, Pena-Correal, & Mauro, 1984), an understanding of the molecular processes controlling choice has been more difficult to determine. For example, Williams (1994) identified two possible response rules that could yield approximate matching at the molar level. One rule assumed that matching was the fundamental process determining responding, so that responses were emitted in proportion to their response strengths. Mazur's (1992) model for acquisition in concurrent schedules provides an example of this approach (see also Grace, 2002). Another possibility is a ''winner-take-all'' rule, in which strengths are computed separately for the different alternatives and responding occurs to whichever alternative has the greater strength at that moment. The sample-and-comparison process assumed by scalar expectancy theory (Gibbon, Church, Fairhurst, & Kacelnik, 1988) represents such a winner-take-all rule. These two types of choice processes are similar to Gallistel and Gibbon's (2000) distinc-

tion between ''opting'' and ''allocation'' processes. They proposed that an allocation process, in which responses were emitted in proportion to their strength, controlled choice on concurrent schedules. For concurrent chains, they suggested that an opting process, in which organisms responded to whichever alternative had the greatest value at that point in time, determined responding.

The clustering of data points evident in the data for Pigeon 221 is consistent with a winner-take-all or opting account of choice (see Figure 10). The argument is similar to that in favor of a categorical discrimination: The clustering suggests that one of two basic response patterns emerged, depending on which terminal-link delay was shorter. Relative responding within each of the clusters, however, was still positively related to relative immediacy.

Another possibility is that the enhanced sensitivity to relative immediacy with green-key delays greater than 8 s is due to the increased overall duration of the terminal links. It is well known that in concurrent chains, preference between a pair of terminal-link schedules in constant ratio becomes more extreme when their absolute duration increases—a finding known as the terminal-link effect (Williams & Fantino, 1978). According to Grace's (1994) contextual choice model, the ratio of the average terminal- to initial-link durations modulates sensitivity to reinforcement immediacy. Because the average terminal-link duration increases as the green-key delay increases, Grace's model predicts that sensitivity should be greater when the green-key delay is greater than 8 s. But this prediction requires that adjustment to overall duration occurs within single sessions, and it is unknown whether these effects occur so rapidly. In addition, Grace's model cannot account for the apparent clustering of data points in Figure 10.

Overall, these experiments demonstrate that initial-link choice of pigeons in concurrent chains can adapt rapidly to daily changes in one of two terminal-link FI schedules. In addition to their potential theoretical significance, these results have procedural import as well. Given the length of training required for steady-state designs (often 30 or more sessions per condition), procedures similar to Experiment 2 can be used to expose subjects

to a large number of delays very quickly. Many questions for future research remain, including whether similar changes in preference would occur if both FI schedules were changed from day to day. These procedures might also shed light on the behavioral processes responsible for molar regularities in choice.

REFERENCES

Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior, 22,* 231–242.

Baum, W. M. (1979). Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior, 32,* 269–281.

Baum, W. M., Schwendiman, J. W., & Bell, K. E. (1999). Choice, contingency discrimination, and foraging theory. *Journal of the Experimental Analysis of Behavior, 71,* 355–373.

Carlson, J. G., & Wielkiewicz, R. M. (1972). Delay of reinforcement in instrumental discrimination learning of rats. *Journal of Comparative and Physiological Psychology, 81,* 365–370.

Davison, M. (1983). Bias and sensitivity to reinforcement in a concurrent-chain schedule. *Journal of the Experimental Analysis of Behavior, 40,* 15–34.

Davison, M., & Baum, W. M. (2000). Choice in a variable environment: Every reinforcer counts. *Journal of the Experimental Analysis of Behavior, 74,* 1–24.

Davison, M. C., & Hunter, I. W. (1979). Concurrent schedules: Undermatching and control by previous experimental conditions. *Journal of the Experimental Analysis of Behavior, 32,* 233–244.

Davison, M., & McCarthy, D. (1988). *The matching law: A research review.* Hillsdale, NJ: Lawrence Erlbaum.

Fantino, E. (1969). Choice and rate of reinforcement. *Journal of the Experimental Analysis of Behavior, 12,* 723–730.

Fleshler, M., & Hoffman, H. S. (1962). A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior, 5,* 529–530.

Gallistel, C. R., & Gibbon, J. (2000). Time, rate, and conditioning. *Psychological Review, 107,* 289–344.

Gallistel, C. R., Mark, T. A., King, A. P., & Latham, P. E. (2001). The rat approximates an ideal detector of changes in rates of reward: Implications for the law of effect. *Journal of Experimental Psychology: Animal Behavior Processes, 27,* 354–372.

Gibbon, J., Church, R. M., Fairhurst, S., & Kacelnik, A. (1988). Scalar expectancy theory and choice between delayed rewards. *Psychological Review, 95,* 102–114.

Grace, R. C. (1994). A contextual model of concurrent-chains choice. *Journal of the Experimental Analysis of Behavior, 61,* 113–129.

Grace, R. C. (2002). Acquisition of preference in concurrent chains: Comparing linear-operator and memory-representational models. *Journal of Experimental Psychology: Animal Behavior Processes, 28,* 257–276.

Grice, G. R. (1948). The relation of secondary reinforcement to delayed reward in visual discrimination learning. *Journal of Experimental Psychology, 38,* 1–16.

Hunter, I., & Davison, M. (1985). Determination of a behavioral transfer function: White-noise analysis of session-to-session response-ratio dynamics on concurrent VI VI schedules. *Journal of the Experimental Analysis of Behavior, 43,* 43–59.

Logue, A. W., Rodriguez, M. L., Pena-Correal, T. E., & Mauro, B. C. (1984). Choice in a self-control paradigm: Quantification of experience-based differences. *Journal of the Experimental Analysis of Behavior, 41,* 53–67.

MacEwen, D. (1972). The effects of terminal-link fixed-interval and variable-interval schedules on responding under concurrent chained schedules. *Journal of the Experimental Analysis of Behavior, 18,* 253–261.

Mazur, J. E. (1992). Choice behavior in transition: Development of preference with ratio and interval schedules. *Journal of Experimental Psychology: Animal Behavior Processes, 18,* 364–378.

Mazur, J. E. (1995). Development of preference and spontaneous recovery in choice behavior with concurrent variable-interval schedules. *Animal Learning & Behavior, 23,* 93–103.

Mazur, J. E. (1997). Effects of rate of reinforcement and rate of change on choice behaviour in transition. *Quarterly Journal of Experimental Psychology, 50B,* 111–128.

Mazur, J. E. (2001). Hyperbolic value addition and general models of animal choice. *Psychological Review, 108,* 96–112.

Mazur, J. E., Blake, N., & McManus, C. (2001). Transitional choice behavior in concurrent-chain schedules. *Behavioural Processes, 53,* 171–180.

Mazur, J. E., & Ratti, T. A. (1991). Choice behavior in transition: Development of preference in a free-operant procedure. *Animal Learning & Behavior, 19,* 241–248.

Schofield, G., & Davison, M. (1997). Nonstable concurrent choice in pigeons. *Journal of the Experimental Analysis of Behavior, 68,* 219–232.

Shettleworth, S. J., & Plowright, C. M. S. (1992). How pigeons estimate rates of prey encounter. *Journal of Experimental Psychology: Animal Behavior Processes, 18,* 219–235.

Stubbs, D. A., & Pliskoff, S. S. (1969). Concurrent responding with fixed relative rate of reinforcement. *Journal of the Experimental Analysis of Behavior, 12,* 887–895.

Williams, B. A. (1994). Reinforcement and choice. In N. J. Mackintosh (Ed.), *Animal learning and cognition* (pp. 81–108). San Diego: Academic Press.

Williams, B. A., & Dunn, R. (1991). Substitutability between conditioned and primary reinforcers in discrimination acquisition. *Journal of the Experimental Analysis of Behavior, 55,* 21–35.

Williams, B. A., & Fantino, E. (1978). Effects on choice of reinforcement delay and conditioned reinforcement. *Journal of the Experimental Analysis of Behavior, 29,* 77–86.

APPENDIX

List of FI schedule values (in seconds) for the green key used in Experiment 2.

Schedule values (s)
2.01
9.13
19.91
2.07
8.68
20.50
11.64
11.41
5.06
3.33
3.12
21.89
15.45
2.16
5.07
10.62
9.11
2.31
4.79
4.85
2.20
21.89
7.86
12.02
5.22
5.90
7.62
2.49
8.38
7.43
6.79
10.50
14.98
14.19
13.19
7.70
29.57
2.33
27.03
2.86
18.38
4.31
3.89
2.40
4.17
13.36
15.15
2.59
16.22
4.30
6.41
13.27
21.88
16.55
3.61
8.07
26.81
8.75
3.01
5.01
7.54